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RECYCLING OF WOOD- AND PEAT-ASH – A SUCCESSFUL WAY TO ESTABLISH FULL PLANT COVER AND DENSE BIRCH STAND ON A CUT-AWAY PEATLAND

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RECYCLING OF WOOD- AND PEAT-ASH – A SUCCESSFUL WAY TO ESTABLISH FULL PLANT COVER AND DENSE BIRCH STAND ON A CUT-AWAY PEATLAND

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Abstract

Mechanical harvesting of peat changes the original mire ecosystem completely, and without active measures these areas may remain non-vegetated even for decades. Afforestation is one of the most popular after-use options for cut-away peatlands in Finland since it has both economic and aesthetic values. Recycling of wood-ash as a fertilizer has been studied extensively in peatlands drained for forestry. Wood-ash is reported to promote tree growth in these areas without any significant negative impact to the environment and could, therefore, be a suitable option also on cut-away peatlands. However, the environmental effects of ash-fertilization on cut-away areas and on ground vegetation are not fully understood.

The impact of wood- and peat-ash application on the early establishment of ground vegetation and downy birch (*Betula pubescens*) seedlings and on post-fertilization element concentrations in plants and peat substrate were studied in a cut-away peatland. Six treatments of wood-ash, peat-ash, biotite or Forest PK-fertilizer were replicated in three blocks in different mixtures and quantities corresponding to 50 kg ha^{-1} of phosphorus.

All the fertilizers accelerated the revegetation of the bare peat surface significantly, whereas the establishment of plants in the unfertilized area was non-existent even several years after the peat harvesting had ceased. The most striking difference between the wood- and peat-ash-fertilizers and the commercial Forest PK-fertilizer was the extensive coverage of fire-loving moss species in all the areas where ash was spread. Wood- and peat-ash application also accelerated the germination and early establishment of downy birch seedlings more efficiently than the PK-fertilizer. Ground vegetation proved to be highly important in increasing the early biomass production and carbon sequestration on ash-fertilized cut-away peatland. In addition, the below-ground biomass was equal to the above-ground biomass, or even greater.

Both wood- and peat-ash fertilization ensured an adequate level of nutrients for the early establishment of ground vegetation and birch seedlings in a cut-away peatland. The mosses and herbaceous plants proved to have a major role in retaining the nutrients and heavy metals that otherwise might have leached away from the ash-fertilized cut-away site during the early stages of the afforestation. Although both wood- and peat-ash proved to be suitable for the initial fertilization of afforested cut-away peatlands, a later application of nutrients may be needed to guarantee the growth in a energy-wood stand of downy birch over its entire rotation.

Keywords: afforestation, Betula pubescens Ehrh., biomass, biotite, carbon stock, fertilization, fire-loving mosses, Forest PK-fertilizer, heavy metals, nutrients, succession

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Tiivistelmä

Turvetuotannon päätyttyä jäljelle jäävä suopohja on aluksi täysin paljas ja vailla maaperän siemenpankkia. Kasvipeitteen luontainen uudistuminen voi viedä jopa vuosikymmeniä. Ympäristönhoidollisesti onkin tärkeää, että suopohjat otetaan uuteen käyttöön mahdollisimman nopeasti tuotannon päätyttyä. Metsitys on tällä hetkellä suosituin suopohjien jälkikäyttömuoto Suomessa. Suopohjan turpeessa on tyypillisesti runsaasti typpeä, mutta niukasti muita kasvuun tarvittavia ravinteita. Puutuhka on osoittautunut pitkäaikaisissa metsäojitettujen turvemaiden tutkimuksissa kilpailukykyiseksi vaihtoehdoksi kaupallisille lannoitteille. Energiantuotannon sivutuotteena syntyvä puu- ja turvetuhka voisi soveltua hyvin myös suopohjien lannoitteeksi. Tuhkan käytöstä lannoitteena turvetuotannosta vapautuneilla suopohjilla ei kuitenkaan ole riittävästi tutkimustietoa.

Tässä työssä tutkittiin puu- ja turvetuhkan vaikutuksia turvetuotannosta vapautuneen suopohjan kasvittumiseen ja puun taimien alkukehitykseen viiden ensimmäisen kasvukauden ajan. Lisäksi tutkittiin kasvillisuuden ravinne- ja raskasmetallipitoisuuksien muutoksia sekä turpeen ravinteisuutta lannoituksen jälkeen.

Kaikki lannoitteet nopeuttivat merkittävästi kasvillisuuden muodostumista paljaalle suopohjalle, kun taas lannoittamaton alue pysyi kasvittomana. Tuhkalannoitetuille alueille syntyi nopeasti laajoja palopaikoilla viihtyvien pioneerisammalten kasvustoja, jotka peittivät ja samalla sitoivat paljaan ja irtonaisen turvemaan pinnan. Tuhkalannoitus edisti myös koivun taimien alkukehitystä tehokkaammin kuin kaupallinen Metsän PK-lannoite. Sammalista ja ruohovartisista kasveista muodostuva aluskasvillisuus ylitti puuntaimet selvästi biomassan määrässä ja toimi metsityksen alkuvaiheessa puuntaimia merkittävämpänä hiilensitojana. Lisäksi kasvien maanalainen biomassa oli maanpäällistä biomassaa suurempi.

Sekä puu- että turvetuhka takasivat riittävän määrän ravinteita energiapuumetsikön alkukehitykselle. Aluskasvillisuus osoittautui tärkeäksi tuhkasta liukenevien ravinteiden ja raskasmetallien sitojaksi metsityksen alkuvaiheessa. Vaikka sammalten kadmiumpitoisuudet nousivat tuhkalannoituksen seurauksena, ne olivat kuitenkin alhaisia Suomessa aiemmin mitattuihin sammalten yleisiin pitoisuuksiin suhteutettuna. Tuhkalannoitus ei lisännyt haitallisten raskasmetallien pitoisuuksia koivun taimien ja ruohovartisten kasvien lehdissä ja varsissa. Tutkimuksen tulokset tukevat puu- ja turvetuhkan käyttöä energiapuumetsiköiden alkuvaiheen lannoitteena turvetuotannosta vapautuneilla suopohjilla.

Asiasanat: biomassa, biotiitti, hieskoivu, hiili, Metsän PK-lannoite, nuotiosammalet, raskasmetallit, ravinteet, sukkessio, suopohjien metsittäminen, tuhkalannoitus

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I started my PhD process in summer 2003 when I was working as a trainee on the joint project “Metsähiisi” that was carried out by the Finnish Forest Research Institute (Metla) Muhos Research Unit and the Vapo Co. At that time, I did the first vegetation inventories at Hirvineva, but I wasn’t yet aware how interesting that research project would be and how far I would eventually go with this research work.

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Oulu, May 2011 Noora Huotari

List of original articles

The thesis is based on the following articles, which are referred to in the text by their Roman numerals:

I Huotari N, Tillman-Sutela E, Kauppi A & Kubin E (2007) Fertilization ensures rapid formation of ground vegetation on cut-away peatlands. Canadian Journal of Forest Research 37: 874–883.

II Huotari N, Tillman-Sutela E, Pasanen J & Kubin E (2008) Ash-fertilization improves germination and early establishment of birch (*Betula pubescens* Ehrh.) seedlings on a cut-away peatland. Forest Ecology and Management 255: 2870–2875.

III Huotari N, Tillman-Sutela E & Kubin E (2009) Ground vegetation exceeds tree seedlings in early biomass production and carbon stock on an ash-fertilized cut-away peatland. Biomass and Bioenergy 33: 1108–1115.

IV Huotari N, Tillman-Sutela E & Kubin E (2011) Ground vegetation has a major role in element dynamics in ash-fertilized cut-away peatland. Forest Ecology and Management 261: 2081–2088.

Author's contribution: N. Huotari planned and carried out the vegetation inventory (I), biomass sampling (III) and collection of the plant samples for carbon, nutrient and heavy metal analyses (III, IV). She participated in birch seedling inventory (II) and in collecting the peat samples (IV). She was responsible for separating the below-ground plant biomass from the peat samples, and for drying and weighing all the biomass samples (III). She also participated in the preparation of the plant samples for the laboratory analyses (III). N. Huotari was responsible for the statistical analyses and was the main author of articles (I-IV).

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1 Introduction

It is estimated that 500 000–600 000 tons of wood- and peat-ash are produced annually as a by-product of energy production and forest industry in Finland (Emilsson 2006, Motiva 2007). Partly due to strict legislation (Ministry of Agriculture and Forestry 2007, 2009), the present practice is to transport the ash to landfills at a considerable cost. Massive promotion of biomass fuels in Europe (Renewable Energy Directive) is expected to further increase the amount of ash produced in power plants, which will cause a significant disposal problem for the industry in the near future. Consequently, decisions regarding cost-effective and environmentally acceptable recycling options remain a priority.

Recycling of wood-ash as a forest fertilizer has been studied extensively in recent decades, mainly in Scandinavia (Karltun *et al*. 2008). In Finland, pure wood-ash has been reported to promote tree growth on peatlands drained for forestry and the effect can be long-lasting, up to 50 years or more (Silfverberg & Huikari 1985, Silfverberg 1996, Moilanen *et al*. 2002). Wood-ash contains all the essential plant nutrients except nitrogen (N), which is vaporized during the combustion (Karltun *et al*. 2008). In addition to the valuable mineral nutrients, wood-ash also contains heavy metals. The use of wood-ash as a forest fertilizer has been questioned mainly because of its cadmium (Cd) content (Pasanen *et al*. 2001, Kepanen *et al*. 2005, Reimann *et al*. 2008). Although studies have shown that pure wood-ash can be used as a fertilizer on peatland forests without any significant negative impacts on the environment (Lodenius 2003, Moilanen *et al*. 2006, Solla-Gullon *et al*. 2006, Saarsalmi *et al*. 2006, Omil *et al*. 2007), the recycling and utilization of wood-ash in these areas is still insignificant.

In addition to wood, peat is also an important domestic fuel in Finland. Large-scale industrial peat harvesting for energy production started in 1970s due to the worldwide oil crisis (Vasander *et al*. 2003). In 2009, 5% of the Finland's total energy consumption was produced by peat and 20% by wood fuels (Official Statistics of Finland 2009). In recent years, large investments have been brought about to enable the integrated use of wood and peat in existing peat-fired power plants (Paappanen & Leinonen 2005). As a result, the actual amounts of mixed-ash and peat-ash generated in power plants are about two-fold compared to pure wood-ash (Motiva 2007). The elemental content of this ash may vary significantly, depending on the fuel and combustion technique (Emilsson 2006). In contrast to wood-ash, peat-ash contains lower levels of harmful heavy metals, such as Cd and Pb, but is also poorer in mineral nutrients (Nieminen *et al*. 2005, Mandre *et al*.

2010). However, the main concern for the use of peat-ash as a forest fertilizer is the relatively low potassium (K) content, which retards tree growth (Hytönen 1998, 2003).

Cut-away peatlands are former mire ecosystems that have been extensively disturbed by the mechanical harvesting process of peat. Peat extraction is usually accomplished in 20–50 years (Nyrönen 1996) and the remaining cut-away area is completely devoid of plants and viable soil seed bank (Salonen 1987, Huopalainen *et al.* 1998). Over the next decade, around 30 000 ha of cut-away peatlands will be abandoned by the peat industry in Finland (Leinonen 2010). Natural revegetation of these cut-away peatlands is extremely slow due to nutrient deficiency and instability of the loose peat substrate (Salonen & Laaksonen 1994, Campbell *et al.* 2002). With no actions, they will remain non-vegetated even for decades (Salonen 1992, Lavoie & Rochefort 1996, Bérubé *et al.* 2000, Lavoie *et al.* 2005).These bare cut-away areas are also a source of atmospheric carbon (Tuittila & Komulainen 1995, Tuittila *et al.* 1999, Alm *et al.* 2007). Thus, in order to diminish the negative impacts to the environment, such as wind erosion and leaching of nutrients and solid matter into watercourses, rapid revegetation of these bare cut-away areas is important.

In Finland, the peat industry operates mainly on leased areas and the landowners decide about the post-harvesting use of the area. Cut-away peatlands have been adapted for agriculture, reed canary grass (*Phalaris arundinacea* L.) cultivation, afforestation, bird sanctuaries and re-paludification (Selin 1999, Vasander *et al.* 2003). At present, afforestation is the most common after-use option in Finland (Holmgren *et al.* 2008), since it has economical, environmental and aesthetic values. Recently, demands for bioenergy and interest in the establishment of dense stands for producing energy wood in short rotations have increased. Downy birch is a common pioneer tree species on moist peat soils in Finland (Päivänen 2007). However, since the residual peat layer on cut-away areas is typically rich in organic N but poor in mineral nutrients, especially phosphorus (P) and K (Paavilainen & Päivänen 1995, Wind-Mulder *et al.* 1996), soil enrichment is needed. In consequence, recycling and utilization of ash as a fertilizer in these areas is a potential option.

Earlier studies on the effect of wood- and peat-ash application on cut-away peatlands have focused mainly on the nutrition and growth of tree species of economic value (Lehtonen & Tikkanen 1986, Hytönen 1998, Hytönen & Kaunisto 1999, Hytönen 2003, Mandre *et al.* 2010), whereas little attention has been paid to the establishment and development of ground vegetation. Although ash-fertilization is reported to be a good ecological solution on peatlands drained for forestry, the impact of ash application on cut-away peatlands may be different, since the residual peat layer is considerably thinner and there is no existing vegetation prior to afforestation. Consequently, before its large-scale processing and recycling as a forest fertilizer can be recommended, an evaluation of the environmental consequences of wood- and peat-ash application is necessary.

2 Aims of the research

The main objective of the present work was to study the possibility to recycle wood- and peat-ash, a by-product of energy production and forest industry, as fertilizers for cut-away peatlands reserved for energy-wood production. The aim of the present work was to find an efficient method to establish dense, short-rotation birch stands on cut-away areas without generating negative environmental impacts. For these purposes, research was carried out to

1. study the effect of wood- and peat-ash application on the establishment of plant cover in a bare cut-away peatland (I)
2. examine the impact of ash application on the germination and early establishment of tree seedlings, especially downy birch (*Betula pubescens* Ehrh.), in a cut-away peatland (II)
3. quantify the biomass and carbon stock of ground vegetation and tree seedlings at the early stages of the afforestation in a cut-away peatland (III)
4. determine the post-fertilization nutrient status of peat substrate and the nutrient and heavy metal contents in plants (IV)
5. assess the post-fertilization nutrient pools in a young birch stand in a cut-away peatland (III, IV and the results presented here)

3 Materials and methods

3.1 Study site

The experimental field was established in 2000 at Hirvineva, in Liminka, Finland (64° 44′ N, 25° 16′ E, 45 m a.s.l.). The cut-away peatland was abandoned by the peat industry in 1996. The residual peat was medium humified moss-sedge peat (SC-p, H5 von Post) with some wood residues, and the thickness of the peat layer varied from 20 to 50 cm. The soil below the peat was sandy till and the groundwater level was about 50 cm. The average yearly temperature sum in the area is 1040 d.d.

The drainage of the experimental area was improved in August 2000 by cleaning the old ditches at 40 m distances. Three blocks were established on the experimental field, and each block was divided into six 40 m x 40 m trial plots (Fig. 1). The plots were split and 1 kg ha^{-1} of downy birch (*Betula pubescens* Ehrh.) seeds was hand-sown on randomized halves on the non-vegetated peat surface in early September 2000. The other halves were left to be afforested by natural seed dispersal.

In May 2001 the following treatments were randomized between the plots and replicated in the three blocks: (1) unfertilized, (2) wood-ash 7.9 t ha^{-1}, (3) mixed-ash 6.3 t ha^{-1}, (4) peat-ash 4.8 t ha^{-1}, (5) peat-ash 4.8 t ha^{-1} + biotite 1.5 t ha^{-}1 and (6) Forest PK-fertilizer 0.5 t ha^{-1} (Table 1). Prior to spreading, the nutrient contents of the ashes were analyzed in the laboratory of the Finnish Forest Research Institute (Metla) at Muhos (IV). The doses of the fertilizers per plot were adjusted corresponding to 50 kg ha^{-1} of phosphorus, as recommended for peatlands drained for forestry (Paavilainen & Päivänen 1995).

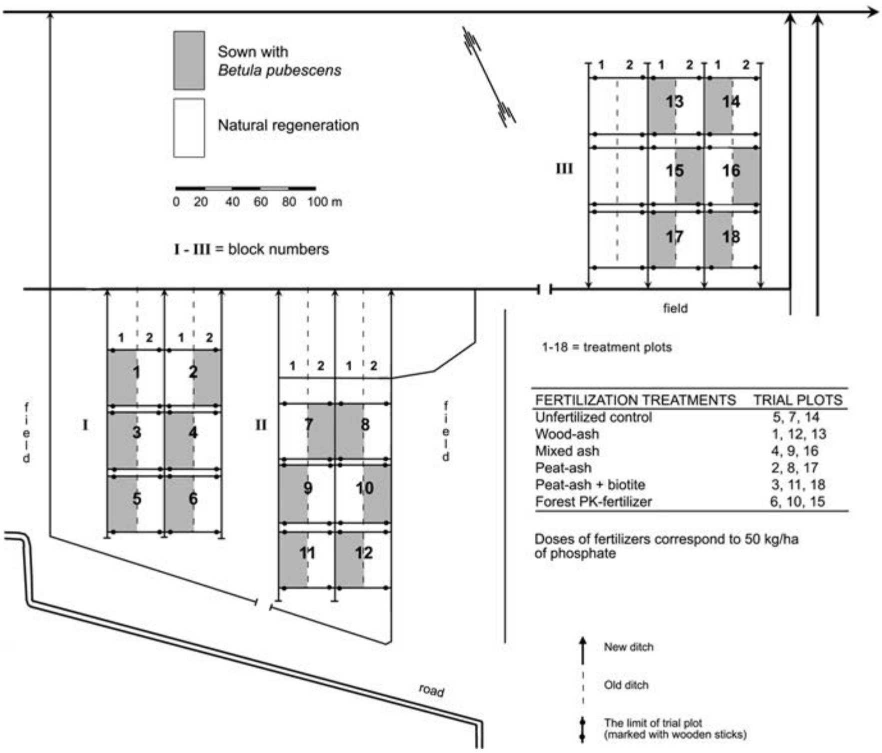

Fig. 1. The experimental field at Hirvineva, Liminka.

Table 1. The amounts (kg ha^{-1}) of the fertilizers used and nutrients applied in the experiment, adjusted to correspond to 50 kg ha^{-1} of phosphorus (P).

		Applied nutrient amounts (kg ha^{-1})				
Fertilization treatments (kg ha^{-1})		N	P	K	Ca	Mg
1) Unfertilized	-	-	-	-	-	-
2) Wood-ash	7874	-	50	161	961	174
3) Mixed-ash	6334	-	50	88	668	128
Wood-ash	3937	-	25	80	188	87
Peat-ash	2397	-	25	8	480	41
4) Peat-ash	4794	-	50	15	376	82
5) Peat-ash + Biotite	6294	-	50	90	481	232
Peat-ash	4794	-	50	15	376	82
Biotite	1500	-	-	75	105	150
6) Forest PK-fertilizer	556	-	50	89	122	-

3.2 Sampling and measurements

Percentage coverage of the tree seedlings and ground vegetation was estimated visually by species in systematically placed square plots (60 cm x 60 cm) in July 2003, 2004 and 2005 (I). The quantity and dominant heights of the established tree seedlings were measured by species in systematically placed circular sample plots yearly 2001–2004 (II). The above-ground biomass of tree seedlings and herbaceous plants was harvested using scissors in systematically placed squares in July–August 2004 (III). The dead plant material (litter) was collected separately. The below-ground biomass of plants was sampled by taking volumetric peat samples from 0–10 cm and 10–20 cm peat layers in the center of the biomass squares. The roots, fine roots and rhizomes were then separated from the peat. Lichens and green parts of mosses were collected from the surface of the peat samples (III). All the plant samples were oven-dried and weighed.

The plant samples for analysis of carbon (III), nutrient and heavy metal (IV) were collected in July 2005. The volumetric peat samples for pH and nutrient analysis were collected from 0–10 cm and 10–20 cm peat layers in systematically placed square plots in August–September 2004 (IV).

3.3 Laboratory analyses

3.3.1 Peat samples

The peat samples were prepared and the nutrient concentrations analyzed at the Metla laboratory in Muhos (IV). The pH was measured by soil-water suspension. The concentration of soluble nitrogen (N) was analyzed from potassium sulphate (0.5 M) extract; the NH_4-N concentration by using a salicylate method and the NO_3-N concentration by reduction with hydrazine- copper sulphate mixture and then measuring the nitrite concentration colorimetrically, following the Finnish standard method (SFS 3029). The concentrations of soluble P, K, Calcium (Ca) and Magnesium (Mg) were analyzed from ammonium acetate (0.5 M) extract; K, Ca, and Mg by using an atomic absorption spectrophotometer (AAS) and PO_4-P by using a spectrophotometer. The determination limits for NH_4-N and NO_3-N were 0.5 mg kg^{-1} and for PO_4-P 1.5 mg kg^{-1}, respectively.

The concentrations of total K, Ca and Mg were determined from the dry-ashed peat samples (dissolved by HCl) by using an atomic absorption spectrophotometer (AAS method). The concentrations of total N were determined by using the Micro-Kjeldahl method (Kubin & Siira 1979) and that of total P photometrically by using the vanado-molybdate method (Halonen *et al*. 1983).

3.3.2 Plant samples

The plant samples for analysis of carbon, nutrient and heavy metal were dried (105 °C), ground to a homogenous powder and digested in HNO_3/H_2O_2 -solution using a microwave oven in the Metla laboratory in Muhos (III, IV). Nutrient and heavy metal (K, P, Ca, Mg, sulphur (S), boron (B), manganese (Mn), zinc (Zn), iron (Fe), copper (Cu), nickel (Ni), Cd, aluminium (Al), lead (Pb)) contents were determined from the solution by ICP-emission spectrometry and C and N from the dry matter using CHN-analyzer in the Metla laboratory in Vantaa. The determination limit for Al was 8.0 mg kg^{-1}, for Cd 0.05 mg kg^{-1} and for Pb 1.50 mg kg^{-1}. The C content 488 g kg^{-1} (Jackson *et al*. 1997) was used in below-ground biomass and 450 g kg^{-1} (Roxburg *et al*. 2006) in litter to estimate the C stock (III).

3.4 Statistical analyses

Statistical methods used for the data analysis were two-way analysis of variance (ANOVA), one-way analysis of variance (ANOVA) with Tukey's multiple comparison tests and Repeated Measures ANOVA. The data that did not meet the assumptions of ANOVA in spite of transformation were tested using a Kruskall–Wallis H test or nonparametric two-factor analysis (by an extension of the Kruskall–Wallis test) with non-parametric Tukey-type multiple comparisons (Nemenyi) tests (Zar 1984). The computer package SPSS for Windows was used for all these statistical tests, with the exception of the nonparametric two-factor analysis with Tukey-type multiple comparisons tests, which was partly manually calculated. The significance level used in all tests was $p < 0.05$.

4 Results

4.1 Total coverage of vegetation

All the fertilizers significantly accelerated the establishment of vegetation in the bare cut-away peatland, whereas the establishment of plants in the unfertilized area was almost non-existent even several years after the peat harvesting had ceased (I and Figs. 2 and 3). Three growing seasons after the fertilization, the small fire-loving mosses, such as *Funaria hygrometrica* (Hedw.) and *Leptobryum pyriforme* (Hedw.) Wils., covered 50–60% of all the ash-fertilized areas, which was 10 times more than in the PK-fertilized areas. During the following two years, the coverage of pioneering moss species gradually decreased on all the fertilized areas as they were replaced by subsequent successional species (I).

Three growing seasons after the fertilization, the coverage of vascular plants in the fertilized areas was 5–8 times greater than in the unfertilized area (I). *Deschampsia cespitosa* (L.) P. Beauv. was by far the most abundant species in all the fertilized areas. At the same time, the dominant species in the unfertilized areas were *D. cespitosa* and *Eriophorum angustifolium* Honck. The total coverage of vascular plants further increased during the following two years in all treatments, but *B. pubescens* displaced *D. cespitosa* as a dominant species in the areas where wood-ash or mixed-ash had been applied.

Fig. 2. The establishment of plants on the unfertilized area was non-existent even several years after peat harvesting had ceased.

Fig. 3. Dense and vigorous vegetation covered the cut-away area three growing seasons after ash application.

4.2 Quantity and growth of tree seedlings

4.2.1 Birch seedlings

Both wood- and peat-ash application significantly promoted the germination and early establishment of downy birch seedlings on a cut-away peatland (II). More than 200 000 birch seedlings per hectare were observed in all the ash-fertilized areas already after the first growing season (in 2001), which was at its best 16 times greater in comparison to the unfertilized area and 2 times greater than in the PK-fertilized area. Three years later, more than 80% of the birch seedlings which had germinated in 2001 were still alive in the fertilized areas, and the total amount of seedlings had even increased due to natural dissemination. At the same time, the number of birch seedlings in the unfertilized plots had decreased drastically and only 14% of the seedlings germinated in 2001 were still alive in 2004. No significant differences in the quantity of birch seedlings were observed between the sown and the naturally regenerated areas.

Fertilization also significantly improved the growth of birch seedlings over the four-year observation period (II). After one growing season, the mixture of wood- and peat-ash resulted in dominant heights four times, and other fertilizers 2–3 times, greater as compared to seedling heights in the unfertilized areas. This difference became further accentuated during the three following years.

4.2.2 Willow and Scots pine seedlings

The number of willow seedlings which established in the fertilized areas in 2001 varied from 50 000 to 80 000 plants per hectare, whereas the quantity in the unfertilized area was on an average 4 000 plants per ha (II). In contrast to birch and willow, the greatest quantity of Scots pine seedlings was in the unfertilized area, about 8 000 plants per ha, while in the fertilized areas their quantity varied from 0 to 3 000 plants per ha.

Wood- and peat-ash fertilizers resulted in willow seedling dominant heights 4–5 times greater compared to the heights in the unfertilized area already after the first growing season, the dominant heights for the Forest PK-fertilizer being 3 times greater (II). The differences between the treatments remained almost unchanged during the observation period.

There were no significant differences in the dominant heights of Scots pine seedlings between the fertilized and unfertilized treatments after the first growing season (II). Three years later, the pine seedlings in the ash-fertilized areas had, however, gained more height than the seedlings in the unfertilized or PK-fertilized areas.

4.3 Plant biomass and C stock

Four growing seasons after the fertilization, the total live, above-ground biomass of ground vegetation, comprising mosses and herbaceous plants, varied among all the ash-fertilized areas from 161 to 231 g m^{-2}, whereas the corresponding biomass in the PK-fertilized area was 108 g m^{-2} and in the unfertilized area was 24 g m^{-2} (III). At the same time, the above-ground biomass of tree seedlings in all the ash-fertilized areas was 73–113 g m^{-2}, in the PK-fertilized area 57g m^{-2} and in the unfertilized area 33 g m^{-2}. The below-ground biomass of herbaceous plants and tree seedlings in the top 20 cm peat layer varied between 197 and 239 g m^{-2} in the fertilized areas, whereas the corresponding biomass in the unfertilized area was 71 g m^{-2}. The amount of plant litter deposited on the ground during the four growing seasons was 101–244 g m^{-2} in the fertilized areas and 34 g m^{-2} in the unfertilized area.

After four growing seasons, the greatest C stock of mosses, on average 55 g m^{-2}, was in the various ash-fertilized areas, whereas the C stock in the PK-fertilized area was only 8 g m^{-2} and in the unfertilized area it was non-existent (III). The corresponding C stock of the above-ground parts of herbaceous plants ranged from 22 g m^{-2} to 51 g m^{-2} in the fertilized areas and was 11 g m^{-2} in the unfertilized area. At the same time, the C stock of tree seedlings was 16 g m^{-2} in the unfertilized areas, on an average 44 g m^{-2} among the ash-fertilized areas and 27 g m^{-2} in the PK-fertilized areas.

The mean C stock of the below-ground parts of herbaceous plants and tree seedlings was 108 g m^{-2} in the fertilized areas and 34 g m^{-2} in the unfertilized area. The C stock in the litter deposited on the ground surface was from 46 g m^{-2} to 110 g m^{-2} in the fertilized areas and 20 g m^{-2} in the unfertilized area.

4.4 Nutrient concentrations in peat

The mean pH-H_2O value of the peat in the unfertilized area was 4.6, while the pH in the fertilized areas was 0.1–0.5 units higher (IV). All the fertilization treatments decreased the concentrations of easily soluble nitrogen, NO_3-N and

NH_4-N, in peat in comparison to the unfertilized area but had no significant effect on the total N concentrations.

Ash-fertilization resulted in 2–6 times higher concentrations of easily soluble phosphorus (PO_4-P) in the 0–10 cm peat layer in comparison to the unfertilized and PK-fertilized areas (IV). The concentrations of PO_4-P were, however, below the reliable detection limit (<1.5 mg kg^{-1}) in a third of the peat samples and, consequently, no statistical tests were applied to the data. Overall, fertilization increased the total P concentrations in the 0–10 cm peat layer compared to the unfertilized area, whereas the concentrations in the 10–20 cm peat layer remained unchanged or even decreased.

All the fertilizers, except peat-ash, doubled the concentrations of easily soluble K in the 0–10 cm peat layer compared to the unfertilized area (IV). At the same time, only the treatment using peat-ash + biotite significantly increased the total K concentrations in peat in comparison to the unfertilized area. Wood-ash, for its part, was the only fertilizer that significantly increased the concentrations of Ca and Mg in peat in comparison to the unfertilized area, and the majority of these nutrients were in easily soluble form.

4.5 Nutrients and heavy metal concentrations in plants

4.5.1 Mosses

The nutrient and heavy metal concentrations in mosses were measured only in the fertilized areas, since there was no moss cover in the unfertilized plots (I, IV). Four years after the fertilization, the P concentration of mosses was significantly higher in the peat-ash fertilized area than in the wood-ash or PK-fertilized areas (IV). At the same time, fertilization had no significant effect on the N and K contents of mosses. Wood-ash increased especially the B contents of mosses in comparison to other fertilizers, and peat-ash especially the Na contents.

The cadmium (Cd) contents of mosses were 2–3 times higher in the ash-fertilized areas than in the PK-fertilized area (IV). At the same time, the concentrations of Al, Cu, Fe and Ni in mosses were higher in the PK-fertilized area than in the ash-fertilized areas. The contents of Pb were below the reliable detection limit (1.5 mg kg^{-1}) in all the treatments.

4.5.2 Herbaceous plants

All the fertilization treatments resulted in significantly decreased N, K, S, Zn and Cu contents in *Deschampsia cespitosa* in comparison to the unfertilized treatment (IV). Fertilization also decreased the concentrations of P, Ca, Fe, Ni and Al, although these differences were not statistically significant. Furthermore, the same phenomenon was observed also concerning the Mg, Mn, Zn and Al contents in other herbs and grasses.

Fertilization either had no significant effect or it decreased the concentrations of heavy metals both in *D. cespitosa* and in other herbaceous plants in comparison to the unfertilized area (IV). The contents of Cd and Pb were below the reliable detection limit in the majority of the herbaceous plant samples.

4.5.3 Birch seedlings

The foliar N contents in all the fertilized areas were comparable to the unfertilized area (IV). All the fertilizers, with the exception of wood-ash, significantly increased the P contents in birch leaves in comparison with the unfertilized treatment. Only the forest PK-fertilizer resulted in significantly increased foliar K contents in comparison to the unfertilized area. In addition, peat-ash + biotite application significantly increased the foliar K contents in comparison to the pure peat-ash. Treatment using peat-ash resulted in higher foliar Ca and Mg concentrations in comparison to the unfertilized area. Overall, the nutrient content in the leaves of birch seedlings was higher than the nutrient content in the stems. None of the fertilization treatments significantly increased the heavy metal concentrations in birch seedlings in comparison with the unfertilized area.

4.6 Nutrient pools in peat and vegetation

The mean biomasses and nutrient concentrations presented in articles III and IV were used to estimate the N, P, K, Ca and Mg pools (kg ha^{-1}) in the top 20 cm peat substrate and in the above-ground parts of birch seedlings and ground vegetation.

Total N pool in the top 20 cm peat layer was abundant in all the treatments, ranging between 7314 and 8991 kg ha^{-1} (Fig. 4a). The P pool of peat varied from 258 kg ha^{-1} in the wood-ash fertilized area to 345 kg ha^{-1} in the PK-fertilized area (Fig. 4c). At the same time, the largest K pool of peat, 100 kg ha^{-1}, was in the treatment which used peat-ash + biotite and the smallest, 53 kg ha^{-1}, in the pure peat-ash treatment (Fig. 4e). The total Ca pool in peat ranged from 2053 kg ha^{-1} in the PK-fertilized area to 3614 kg ha^{-1} in the mixed-ash fertilized area (Fig. 5a). The Mg pool of peat was 298 kg ha^{-1} in the PK-fertilized area and varied between 405 and 494 kg ha^{-1} among the other treatments (Fig. 5c). The proportions of easily soluble N and P in peat were 1% or less of the total pools (Figs. 4a–d). At the same time the corresponding share for K, depending on the treatment, was 28–68% (Fig. 4e–f), for Ca 67–74% (Fig. 5a-b) and for Mg 72–93% (Figs. 5c–d).

The amounts of N, P, Ca and Mg bound in the above-ground plant biomass made up only 1% or less of the total pools in the peat substrate in all the treatments (Figs. 4a, 4c, 5a, 5c), whereas the corresponding share for K was 5% in the unfertilized area and varied from 18% to 40% in the fertilized areas (Fig. 4e). In comparison with the soluble nutrients in peat, the amounts of N, P and K bound in plant biomass were consistently high in all the fertilized areas (Figs. 4b, 4d, 4f).

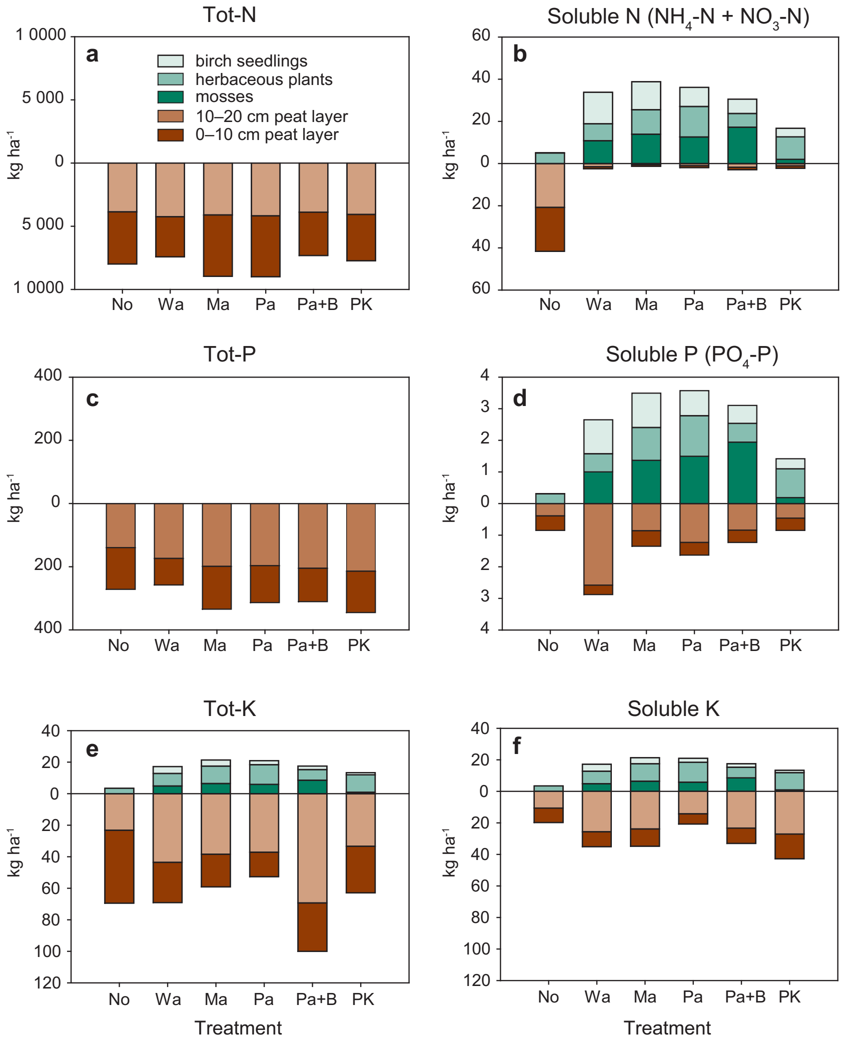

Fig. 4. The total (a, c, e) and soluble (b, d, f) N, P and K pools (kg ha^{-1}) in peat in relation to the amounts bound in above-ground plant biomass in the six fertilization treatments. No=unfertilized, Wa=wood-ash, Ma=mixed-ash, Pa=peat-ash, Pa+B=peat-ash+biotite, PK=Forest PK-fertilizer. The nutrient pools were calculated on the basis of the biomass figures and nutrient concentrations presented in articles III and IV.

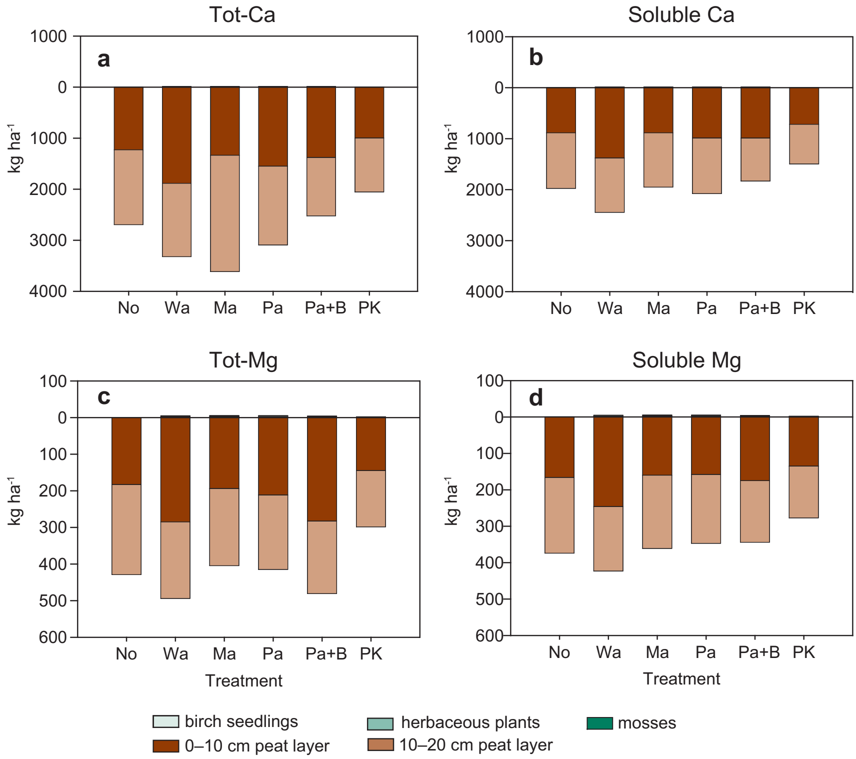

Fig. 5. The total (a, c) and soluble (b, d) Ca and Mg pools (kg ha^{-1}) in peat in relation to the amounts bound in above-ground plant biomass in the six fertilization treatments. No=unfertilized, Wa=wood-ash, Ma=mixed-ash, Pa=peat-ash, Pa+B=peat-ash+biotite, PK=Forest PK-fertilizer. The nutrient pools were calculated on the basis of the biomass figures and nutrient concentrations presented in articles III and IV.

5 Discussion

Both wood- and peat-ash fertilization ensured a rapid formation of dense ground vegetation on a cut-away peatland, whereas the establishment of plants in the unfertilized areas was sparse even several years after the cessation of peat harvesting (I). Interestingly, ash-fertilizers in particular increased the coverage of fire-loving moss species, such as *Funaria hygrometrica* (Hedw.) and *Leptobryum pyriforme* (Hedw.) Wils., whereas their cover in the PK-fertilized and unfertilized areas was insignificant. The colonization of moss species on the bare ash-fertilized cut-away area resembled a process after severe natural fire (Rees & Juday 2002, Ryömä & Laaka-Lindberg 2005). Furthermore, the ash itself appeared to have a greater impact on the colonization success of fire-loving mosses than did open space or improved nutritional conditions (I), even if the aerial diaspore dispersal ability of mosses in harvested peatlands is reported to be high (Campbell *et al*. 2003). This result indicates that in addition to nutrients, there are also other components in plant-derived ash, comparable to those found in plant-derived smoke (Dixon *et al*. 2009), that promote the germination of different plant species.

Ash application in particular also improved the germination and early establishment of downy birch (*Betula pubescens* Ehrh.) in a cut-away peatland (II). As a pioneer species, birch in many cases colonizes bare grounds rapidly. However, drought and instability of the loose peat surface on bare windswept cut-away areas do not favor the establishment of plants (Salonen *et al*. 1992, Salonen 1994, Cambell *et al*. 2002). In addition, frost heaving is reported to complicate the rooting and survival of young tree seedlings in open cut-away peatlands (Groeneveld & Rochefort 2002, Lavoie *et al*. 2005). The newly risen moss cover in the ash-fertilized areas apparently formed a favorable germination ground for the birch seeds by stabilizing the loose erodible substrate and the moisture content of the peat surface (I, II). On the other hand, the quantity of Scots pine seedlings was more than three times higher on the unfertilized areas compared to the ash-fertilized areas (II), which confirmed the reported retarding effect of ash on the germination of pine seeds (Rikala & Jozefek 1990, Reyes & Casal 2004). In fact, the germination response of plants to fire, smoke or ash varies between species and may therefore influence the species composition in post-fire succession (Gonzáles-Rabanal & Casal 1995, Zuloaga-Aguilar *et al*. 2011).

The quantities of birch seedlings which germinated in 2001 remained high and almost unchanged during the four-year observation period in all the fertilized areas, whereas the number of original birch seedlings in the unfertilized area decreased drastically (II). Fertilization also increased the dominant heights of the birch seedlings in comparison to the unfertilized treatment. Surprisingly, the dense herbaceous vegetation, comprised mainly of *Deschampsia cespitosa*, seemed to facilitate rather than prevent the early development of birch seedlings (I, II). This was probably due to a more stable microclimatic temperature and moisture conditions within the vegetation, which protected the birch seedlings from wind and spring and autumn frosts. The results thus confirm the importance of facilitation in the succession mechanism of plant colonization of harvested peat surfaces (Tuittila *et al*. 2000, Groeneveld & Rochefort 2005, Koyama & Tsuyuzaki 2010).

The results proved that the post-fertilization above-ground biomass of mosses and herbaceous plants was up to two times greater than the above-ground biomass of tree seedlings (III). A rough estimation of the amount of C fixed by the above-ground parts of the herbaceous plants in the ash-fertilized areas was 35 g C m^{-2} a^{-1}, and by mosses 14 g C m^{-2} a^{-1}. Since the above-ground parts of herbaceous plants represent one year's growth (Mälkönen 1974), the standing biomass of herbaceous plants measured here was assumed to be equal to their annual above-ground production (III). The annual production of mosses was assumed to be a quarter of the standing biomass that they had built up during the four post-fertilization growing seasons. In the present life cycle analysis (LCA) of peat fuel utilization chains, only C fixed by the growing trees is used when estimating the C balance in afforested cut-away peatlands (Kirkinen *et al*. 2007, Hytönen et al. 2008). However, the total amount of C fixed by the above-ground parts of the ground vegetation in this study was at least 15% of the quantities (45–330 g C m^2 a^{-1}), that are used in the actual calculations. Those quantities do not include the C bound in the ground vegetation and deposited litter, due mainly to the absence of exact studies. Since the role of stand age is of great importance when explaining the variation of plant biomass during succession process (Muukkonen & Mäkipää 2006), the biomass figures presented in this study are consistent only with the early stages of the afforestation process. Therefore, empirical data on the entire forest vegetation growth during the rotation period in afforested cut-away areas is needed.

The present results showed also that the below-ground biomass of plants, i.e. roots and rhizomes, was equal to the above-ground biomass, or even greater (III). This is in accordance with earlier findings in boreal forests, where more than 70% of the field layer biomass is reported to be in roots (Palviainen *et al*. 2005). Fine-roots are reported to produce the majority of the annual biomass in tree stands of varying ages (Helmisaari *et al*. 2002). Thus, the total annual C sequestration of ground vegetation may be considerably larger than estimated above (III). The decomposition rates of different types of plant litter, e.g. root litter and leaf litter vary. Therefore, the ratio of litter input to decomposition output should be measured, when attempting to assess the overall effect of ground vegetation on C balance.

All the fertilizers ensured an adequate level of nutrients in the top 20 cm peat layer for the early establishment and growth of vigorous ground vegetation and tree seedlings in a cut-away peatland (IV). In previous studies, successful tree growth in cut-away areas is reported to be limited mainly by low levels of P and K in the peat substrate (Lumme 1988, Hytönen 1994, Aro *et al*. 1997). The present results proved that four years after the fertilization the P concentrations in birch leaves in all the fertilized areas were even higher than the average values reported for varying aged birches not suffering from P deficiency (Ferm and Markkola 1985, Sarjala & Kaunisto 2002). At the same time, the foliar K concentrations of the vigorous birch seedlings in the areas fertilized with mixed-ash or peat-ash were near the potassium deficiency level reported for older birches in cut-away peatlands (Sarjala & Kaunisto 2002, Kaunisto & Sarjala 2003). This implies that the nutrient demands of trees vary at different ages and that, at later stages, deficiency of K may be a limiting factor for tree growth. On the other hand, the dilution effect due to increased biomass may also have decreased the nutrient concentrations in birch leaves. For the further evaluation of nutrient sufficiency over the planned 30-year rotation, the nutrient pools in peat and plant biomass were calculated.

The total N pool in peat was large in comparison to the amounts bound in the above-ground plant biomass (Fig. 4a), which indicates a low risk for future N deficiency. Even if ash itself contains no N, application of ash is reported to accelerate the mineralization of organically bound N in peat due to a rise in pH and bacterial activity (Weber *et al*. 1985, Hytönen 1998, Moilanen *et al*. 2002, Mahmood *et al*. 2003, Pitman 2006 and references within). Furthermore, ground vegetation proved to have a major role in retention of the available N in peat (Fig. 4b) that otherwise could have leached from the unvegetated cut-away peatland area during the early stages of the afforestation (IV). Also, the total P, Ca and Mg stores in peat were abundant in relation to the demands of plants (Figs. 4c, 5a, 5c). However, since only 1% or less of the total P reserve was in easily soluble form and thus readily available for plants, the sufficiency of P for tree growth in the long term is largely determined by the rate of mineralization.

At the same time, the total K pools in peat were rather scant in all the treatments, except in that of peat-ash + biotite, which implies a potential risk for future deficiency. On the other hand, the K bound in the plant biomass contributed considerably to the total K store of the site. Since K is characterized by high mobility both in peat soils (Rydin & Jeglum 2006) and within plants (Marschner 1995), its biological cycling is efficient and leaching losses usually insignificant (Laiho *et al*. 1999). Thus, even limited K pool may be sufficient for tree growth for the planned 30-year rotation period. Furthermore, the tree roots may penetrate the sub-peat mineral soil within some years and the K deficiency of trees can thus be minimized.

Interestingly, the K store in the area fertilized with pure peat-ash was almost equal to the K store in the area fertilized with wood-ash, even if the amounts of K applied with wood-ash treatment was ten times larger in comparison with that of the peat-ash. Thus, the post-fertilization concentrations of easily soluble K in the wood-ash fertilized area apparently exceeded the sequestration capacity of the vegetation and resulted in leaching of the excess K to the lower soil layers. The solubility of K in peat-ash is reported to be considerably lower than in wood-ash (Nieminen e*t al*. 2005), which probably minimized the leaching losses in the peat-ash fertilized area and equalized the fertilization effects of wood- and peat-ash.

The post-fertilization concentrations of Cd and other harmful heavy metals varied among the studied plant groups (IV). The Cd contents in mosses in the ash-fertilized areas were 2–3 times higher than in the PK-fertilized area, whereas the concentrations of Cd and other harmful heavy metals in the shoots of herbaceous plants and birch seedlings remained at low levels despite the ash application. However, the levels of Cd and other harmful heavy metals were relatively low in comparison with the average concentrations measured in mosses in Finland (Poikolainen *et al*. 2004). The main path for elements' uptake in rootless mosses is through the leaves, and contact with upper soil layer is reported to have a major influence on their chemical composition (Reimann *et al*. 2001). Unlike mosses, herbaceous plants and trees absorb nutrients mainly from the soil via their roots. Consequently, the unchanged levels of Cd and other heavy metals in the tissues of vascular plants observed here may be due to differences in the heavy metal concentrations between the above- and below-ground parts of the plants, as has been reported in tree seedlings in the laboratory conditions (Österås *et al*. 2000).

However, the impact of ash-application on the heavy metal levels in the roots of herbaceous plants or trees is not extensively studied.

The present results indicated that dense pioneer moss cover was important in trapping the heavy metals, such as Cd, present in ash (IV). Thus, due to their great biomass (III) and consistently slow decomposition rate in comparison to the herbaceous plants (Lang *et al*. 2009, Turetsky *et al*. 2010), mosses may be more important than previously estimated in preventing the fast recycling of Cd in the ecosystem. These findings were contrary to earlier studies in which wood-ash was applied onto the existing moss cover in mature forests and no significant change in the heavy metal concentrations of mosses was found, even if the moss cover suffered severely from direct contact with large quantities of ash (Jacobson & Gustafsson 2001, Moilanen *et al*. 2002, Ozolinčius & Varnagirytė 2005, Ozolinčius *et al*. 2007). In this study, the ash was spread on the bare peat surface, which favored the colonization of moss species adapted to post-fire conditions, such as *Ceratodon purpureus*, *Funaria hygrometrica* and *Leptobryum pyriforme* (I).

Low levels of Cd (1–5 ppm) are reported to stimulate the germination and early growth of *F. hygrometrica*, whereas higher levels inhibit the germination process completely (Lepp & Roberts 1977). Also Cu, Pb and Zn are known to inhibit the germination and growth of several moss species even at considerably low levels (Francis & Petersen 1989, Tyler 1990 and ref. within) and the same phenomenon has been reported also in some herbaceous plant species (Lefèvre *et al*. 2009). Consequently, since the Cd tolerance levels of *F. hygrometrica* are known to be quite finite, it could be considered as an indicator species for low levels of soluble Cd in the growing substrate.

6 Conclusions and future prospects

Natural regeneration together with wood- and peat-ash application proved to be an efficient way to establish a dense birch stand for energy-wood production in a cut-away peatland. Ash itself had a greater impact on the colonization success of several pioneering species, such as fire-loving mosses and birch, than did open space or artificial fertilization.

The establishment of dense ground vegetation of mosses and herbaceous plants in all the ash-fertilized areas had several environmental advantages. The vegetation stabilizes the loose peat surface and decreases erosion and leaching of nutrients and solid matter into watercourses. The vigorous ground vegetation also facilitated rather than prevented the early growth of birch seedlings in a cut-away peatland and should thus be given consideration when afforesting such areas.

The dense ground vegetation was important also in the biomass production and C sequestration at the early stages of the afforestation. However, the long-term dynamics of ground vegetation and litter accumulation in afforested cut-away areas are not well known. To enable more accurate calculations on the C balance in afforested cut-away peatlands for life cycle analysis and climate impact studies, vegetation inventories and biomass measurements at different succession stages, e.g. at five-year intervals, are needed.

Both wood- and peat-ash ensured an adequate level of nutrients for the early establishment and growth of ground vegetation and birch seedlings in a cut-away peatland. However, a later application of nutrients, especially K, may be needed to guarantee successful tree growth over the entire 30-year rotation. Also, future harvesting of energy-wood may disturb the nutrient balance of the forest stand and retard the establishment of second tree generation. Therefore, the nutrient status of the plant community should be measured at ten-year intervals. Information about the stand’s nutrient status could be accumulated not only by the measurement of the nutrients in peat and in the leaves of trees, but also in ground vegetation.

The dense pioneer moss cover was important in trapping the heavy metals present in the ash, whereas the levels of Cd and other harmful heavy metals remained at low levels in the shoots of herbaceous plants and birch seedlings. Due to the dilution effect of vigorous vegetation, the post ash-application Cd levels in herbaceous plants were even below the determination limits and in birch seedlings below the natural levels. However, studies on the concentrations in the roots of trees and herbaceous plants are needed for a more complete view of the heavy metal levels in plants after ash-application.

The results support the use of wood- and peat-ash as fertilizers for the afforestation of cut-away peatlands. The recycling of ash would provide an environmentally sustainable way for producing energy-wood in these areas. In addition, rapid establishment of dense vegetation increases the C fixation into the ecosystem and may simultaneously reduce atmospheric carbon dioxide emissions from bare cut-away areas. However, grading and stabilization of the nutritional quality of ashes prior to granulation or pelletizing is a pre-requisite for large-scale use of ash as a forest fertilizer.

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Original articles

The thesis is based on the following articles, which are referred to in the text by their Roman numerals:

I Huotari N, Tillman-Sutela E, Kauppi A & Kubin E (2007) Fertilization ensures rapid formation of ground vegetation on cut-away peatlands. Canadian Journal of Forest Research 37: 874–883.

II Huotari N, Tillman-Sutela E, Pasanen J & Kubin E (2008) Ash-fertilization improves germination and early establishment of birch (Betula pubescens Ehrh.) seedlings on a cut-away peatland. Forest Ecology and Management 255: 2870–2875.

III Huotari N, Tillman-Sutela E & Kubin E (2009) Ground vegetation exceeds tree seedlings in early biomass production and carbon stock on an ash-fertilized cut-away peatland. Biomass and Bioenergy 33: 1108–1115.

IV Huotari N, Tillman-Sutela E & Kubin E (2011) Ground vegetation has a major role in element dynamics in ash-fertilized cut-away peatland. Forest Ecology and Management 261: 2081–2088.

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Original publications are not included in the electronic version of the dissertation.

560. Siirtola, Antti (2010) Algorithmic multiparameterised verification of safety properties : process algebraic approach

561. Lappi, Anna-Kaisa (2010) Mechanisms of protein disulphide isomerase catalyzed disulphide bond formation

562. Sarala, Marian (2010) Elongation of Scots pine seedlings under blue light depletion

563. Vance, Anthony (2010) Why do employees violate is security policies? : insights from multiple theoretical perspectives

564. Karppinen, Katja (2010) Biosynthesis of hypericins and hyperforins in *Hypericum perforatum* L. (St. John's wort) – precursors and genes involved

565. Louhi, Pauliina (2010) Responses of brown trout and benthic invertebrates to catchment-scale disturbance and in-stream restoration measures in boreal river systems

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